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Geology of amethyst quartz deposits from Montezuma and surrounding areas of Minas Gerais and Bahia States

Geologia dos depósitos de quartzo ametista de Montezuma e adjacências em Minas Gerais e Bahia

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Abstract

Amethyst quartz deposits occur in some regions of Minas Gerais state, Brazil, related to different geological environments. The most important are associated with hydrothermal veins crossing the Espinhaço mountain range, mainly in small and eroded mountains near its east margin, related to the Macaúbas Group. In the border region between the states of Minas Gerais (MG) and Bahia (BA), some of these deposits produce amethyst crystals that become green under heat treatments and are known in the gemmological market as "prasiolite." The aim of the present study was to provide details of the clear structural control over the mineralized veins. The quartz veins are hosted in quartzites, which have long been the subject of controversy regarding their stratigraphic position. In this study, they are inserted into the Santo Onofre (MG) and Serra de Inhaúma (BA) sequences of unknown ages. These quartzites show a folded subvertical foliation, indicating a posterior deformational phase that had not been observed in rocks from the Macaúbas Group in other regions of MG state. At the Montezuma mine (MG), the main veins are around 0.70-1.10 m thick with steep dips to the NE, perpendicular to the NE-SW foliation; bedding orientation is approximately N-S, dipping to the E. In the Coruja mine area (BA), host quartzites have foliation attitudes varying between N35-45°E/subvertical, and mineralized veins are around 1 m thick, nearly concordant with the foliation. At Tibério's mine (BA), the mineralization is related to narrow fractures, less than 30 cm wide, and perpendicular to the host quartzite foliation, with directions/dips around N20°W/80°SW. In described deposits, amethyst veins occur structurally related to axial surfaces in foliation folds.

Keywords: Mineral deposits; Quartz veins; Prasiolite; Hydrothermal deposits.

Resumo

Depósitos de quartzo ametista ocorrem em diversas regiões do estado brasileiro de Minas Gerais, relacionados a diferentes ambientações geológicas. Os mais importantes associam-se com veios de quartzo hidrotermal que cortam a Serra do Espinhaço, principalmente em serras pequenas, erodidas, próximas à sua margem leste, relacionadas ao Grupo Macaúbas. Na região limítrofe entre os estados de Minas Gerais (MG) e Bahia (BA), alguns desses depósitos produzem cristais de ametista que se tornam verdes após processo de aquecimento, comercializados no mercado gemológico como "prasiolita". O objetivo deste trabalho foi apresentar um detalhamento do nítido controle estrutural para os veios mineralizados. Os veios de quartzo estão hospedados em quartzitos que desde longa data possuem posicionamento estratigráfico controverso. Nesse artigo, eles são associados às sequências Santo Onofre (MG) e Serra de Inhaúma (BA), de idades desconhecidas. Tais quartzitos mostram uma foliação subvertical dobrada, revelando uma fase deformacional posterior não observada em rochas do Grupo Macaúbas em outras regiões de MG. Na mina Montezuma (MG) os veios principais têm por volta de 0,70-1,10 m de espessura, com mergulhos acentuados para NE, perpendiculares à foliação NE-SO; acamamento pouco evidente está em torno de N-S mergulhando para L. Na mina Coruja (BA), os quartzitos hospedeiros também apresentam foliação subvertical variando entre N35-45°E, com veios mineralizados em torno de 1 m de espessura concordantes com a foliação. Na mina Tibério (BA), a mineralização é relacionada a fraturas estreitas, menores que 30cm, perpendiculares à foliação dos quartzitos encaixantes, com atitudes em volta de N20°O/80°SO. Nesses depósitos, os veios de ametista ocorrem estruturalmente relacionados aos planos axiais das grandes dobras da foliação.

Palavras-chave: Depósitos minerais; Veios de quartzo; Prasiolita; Depósitos hidrotermais.

INTRODUCTION

Amethyst quartz deposits occur in different regions of Minas Gerais and Bahia states, associated with distinct genetic environments (Chaves and Favacho-Silva, 2000; Dias et al., 2019). Among those genetic environments, the most important one is related to hydrothermal quartz veins crossing the Proterozoic lithostratigraphic units that form the Espinhaço Mountain Range, mainly in the minor mountains located at its eastern border.

Montezuma's amethyst quartz deposit in Minas Gerais (MG) has been known since the 1930s. It is internationally renowned due to the fact that amethysts from Montezuma become greenish, transparent, or translucent upon heating. This fact was mentioned for the first time by Pough (1957). The visually attractive olive green color has been used by the gemological market under the name "prasiolite." There is no report of any other place worldwide where amethyst undergoes transformation of this type, except for the nearby and lesser-known Coruja deposit in Condeúba municipality, Bahia (BA) state, where amethyst also shows such a color change. In contrast, amethyst from the Tibério deposit in the Cordeiros municipality, BA, loses color without going green or yellow. Both deposits in Bahia are also described herein.

All of these deposits have been regularly mined since the 1960s. The Montezuma mine is currently at a standstill, while the Condeúba and Cordeiros Bahian mines are in full operation. The aims of this article were to provide details of the vein swarms that produce the amethyst, as well as show the clear structural control and mineralogy of the deposits. The problem of the host geological sequence in those three deposits is discussed according to the different geological maps available.

REGIONAL GEOLOGY

Along the border between MG and BA states, the Espinhaço Mountain Range rises up in a narrow belt predominantly composed of strongly folded and eroded quartzites of the Espinhaço Supergroup (Mesoproterozoic). At the eastern edge of the mountain range, some sequences of metasediments occur, which have long been the subject of controversy regarding their stratigraphic positions (Figure 1).

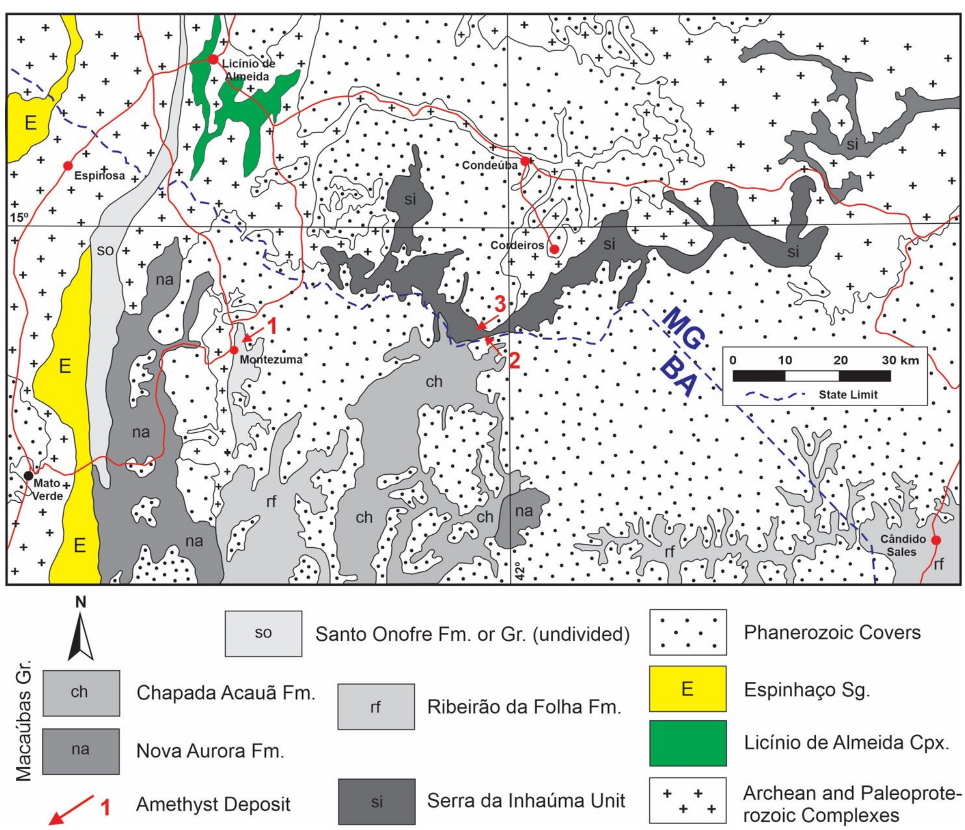


Figure 1. Geology of the neighboring region between the MG and BA states with several recognized units of the Macaúbas Group (Neoproterozoic) highlighted in shades of gray, and the "Serra de Inhaúma" (Paleoproterozoic?) and "Santo Onofre" (Neoproterozoic) sequences within this context (according to Souza et al., 2009a, 2009b, respectively Brasília and Salvador sheets, partial and modified). Amethyst deposits: 1, Montezuma (MG); 2, Coruja (BA); and 3, Tibério (BA).

The Montezuma (MG), Coruja, and Tibério (BA) amethyst deposits are hosted in these quartzite and schist metasediments, which outcrop along the MG-BA border. Earlier regional geological mapping already demonstrated a correlation problem regarding stratigraphic interpretations between the two states. Specifically, the authors of the MG geological map (scale 1:1,000,000; Heineck et al., 2003) located the Montezuma area in MG in the Macaúbas Group, a "post-Espinhaço Supergroup" unit of Neoproterozoic age, while Inda and Barbosa (1978) in BA have inserted the correlative sequence in the "Licínio de Almeida Complex" (a "Pre-Espinhaço Supergroup" unit) of possible Archean age.

Older mapping of the Brasília Sheet at the same 1:1,000,000 scale (Bruni and Schobbenhaus Filho, 1976) by the Departamento Nacional de Produção Mineral (DNPM) addressed both the Montezuma amethyst mine (MG) and a "mineralized area" of amethyst deposits on the Bahian side of the border. Those authors included classic Espinhaço quartzites and another unit, informally designated as "Borda Leste" sequence (where such amethyst mineralization occurs), in the context of the Espinhaço Supergroup. Otherwise, the subsequent Radambrasil Project (Fernandes et al., 1982) mapped the amethyst deposits of the border area as belonging to the Macaúbas Group in MG, and to the "Serra de Inhaúma Group," a quartzite unit of uncertain age, in BA.

As for the most recent available mappings, a contradictory approach still remains. Thus, in the case of MG, Pinto and Silva (2014) inserted the rocks of the Montezuma area in the Santo Onofre Group, which was described further to the south as a unit of the Macaúbas Group (Viveiros et al., 1979; Noce et al., 1997). In contrast, the most recent Map of Brazil at 1:1,000,000 scale (Souza et al., 2009a, 2009b) included the amethyst deposits as a member of the Nova Aurora Formation (Macaúbas Group). This formation disappears toward the north in BA and is replaced by the "Serra Inhaúma Unit" as an informal stratigraphic sequence (Souza et al., 2009a, 2009b).

In contrast, Uhlein et al. (2007) recognized the similarity between the lithostratigraphic sequences between both states, when they identified the "Macaúbas-Santo Onofre Rift" in geotectonic terms, with local geological differences that are more related to their geotectonic positioning in relation to the São Francisco Craton than to their stratigraphic frameworks. When joining the sequences on either side of the border, these authors highlighted the common existence of metadiamictites of glacial origin, which were attributed to the Sturtian glaciation (± 750 Ma). In the other way, recent geochronological data from Babinski et al. (2012) showed that the Macaúbas metadiamictites were deposited at an age older than 850 Ma (U-Pb in detrital zircons), implying that they formed during the Early Cryogenian glacial event.

Therefore, the problem of the geological connection between the MG and BA states remains open. In the present study, the authors prefer to maintain the amethyst deposits within the Macaúbas Group, as classically described on the eastern edge of the Espinhaço mountain range in MG, especially since the lithostratigraphic association present in the area resembles those previously studied farther toward the south by one of the authors in the regions of Grão Mogol (Chaves et al., 1999), Capelinha/Itamarandiba (Chaves et al., 2017), and Felício dos Santos (Chaves and Coutinho, 1992), all of which possess important hydrothermal amethyst deposits.

At the regional scale, the main quartz vein mineralizations are associated with the Brasiliano tectonothermal event, developed during the end of the Neoproterozoic age (Chaves et al., 2010, 2018; Pedrosa-Soares et al., 2011).

METHODOLOGY

Extensive geological fieldwork has been conducted in the region where the amethyst deposits occur. In both states of MG and BA, the geological structures of Espinhaço Range generally have directions around north-south, and thus mapping profiles of east-west direction were conducted. A more detailed structural study was done in the Montezuma deposit area, which allowed the construction of a stereogram that showed the main structural trends.

In the locations of the three visited mines, selected samples were collected for further mineralogical studies. In this context, heat treatments were carried out on samples from the focused mines. Such preliminary experiments were carried out in a muffle furnace in the heavy minerals laboratory of the Centro de Pesquisa Prof. Manoel Teixeira da Costa of the Instituto de Geociências of the Universidade Federal de Minas Gerais (CPMTC-IGC/UFMG), with a 50°C temperature increase every 3 h up to 600°C.

GEOLOGY OF THE AMETHYST DEPOSITS

Montezuma (MG)

Montezuma is an ancient and important mine, first described by Moraes (1936), who recognized its local denomination as "Anta Gorda," situated in Tábua Farm (GPS-UTM 771509E and 8322350N, 23L), 5 km northeast of the Água Quente village, which nowadays corresponds to the Montezuma municipality (Figure 2A). At that time, however, that locality belonged to the Rio Pardo de Minas municipality. The mining operation was conducted by Badin Mining Company, from Rio de Janeiro, and is now interrupted.

The quartzites discussed in the previous section outcrop extensively around Montezuma, although they do not form expressive elevations (Figure 2B). The rocks consist of fine-grained, white quartzites, which show recrystallization and are quite friable locally. Ruin-shaped landscapes are common on outcrops. The main structural feature of these rocks is their strong and intensely folded subvertical foliation. Immediately southeast from the city, at the touristic locality known as Lapinha, it is observed that such foliation, between N15-30°E and 75-85°NW, almost entirely obliterates the rock bedding, which is between N60-80°W and 15-25°SW. Quartz veins are absent in this area. It is emphasized that the folds in the quartzite foliation reveal a deformational phase that had not been observed in rocks from the Macaúbas Group in Minas Gerais.

Source: photos by M. L. S. C. Chaves.

Figure 2. (A) View of the Montezuma town from the Anta Gorda amethyst mine. (B) Host quartzite of the mineralized veins, showing the gentle bedding. (C) The mine main gallery entrance (NNE direction). (D) Pile of amethyst samples which turned greened due to long-term sun exposure.

At the mine entrance gallery (Figure 2C), the quartzites are petrographically similar to those from the Lapinha and have a foliation ranging between N15-30°E and 65-75°SE, which denotes their sudden variation within a short distance. The bedding also changes to around N20°E/20°SE, distinct from that observed at Lapinha. According to several authors (e.g., Bruni and Schobbenhaus Filho, 1976; Cassedanne and Cassedanne, 1976), the main veins are around 0.70-1.10 m thick and have attitudes around N30-45°W/subvertical. Abundant piles of mining tailings are present in the surroundings, where crystals became greenish by long exposure to sunlight (Figure 2D).

As seen in a recent Google Earth view from the mineralized area, the veins occur along the NE-SW hinge line of a tight isoclinal fold disrupted to the east (Figure 3A). The quartz veins were mined for at least 100 m along that direction. A detailed structural study was carried out perpendicularly to the folding axis regarding the foliation observed in the mentioned image, whose data are represented in the stereogram of Figure 3B. These data confirmed such fold and its ENE general direction. As already mentioned, the bedding can only be observed locally, not allowing to obtain numerical data for its statistical representation.

Cassedanne and Cassedanne (1976) described the four main vein swarms, named Alberto, Waldir, Três Faces, and Seis Faces (the last two mean, respectively, three faces and six faces). Those veins are formed by crystals grown roughly perpendicular to the contacts, and they can be more than 20 cm long in larger druses, which are marked by the enlargement of the vein and serve as guides to the miners. Additionally, those authors have pointed out that each mineralized fracture zone is characterized by having only one type of crystal: with terminal

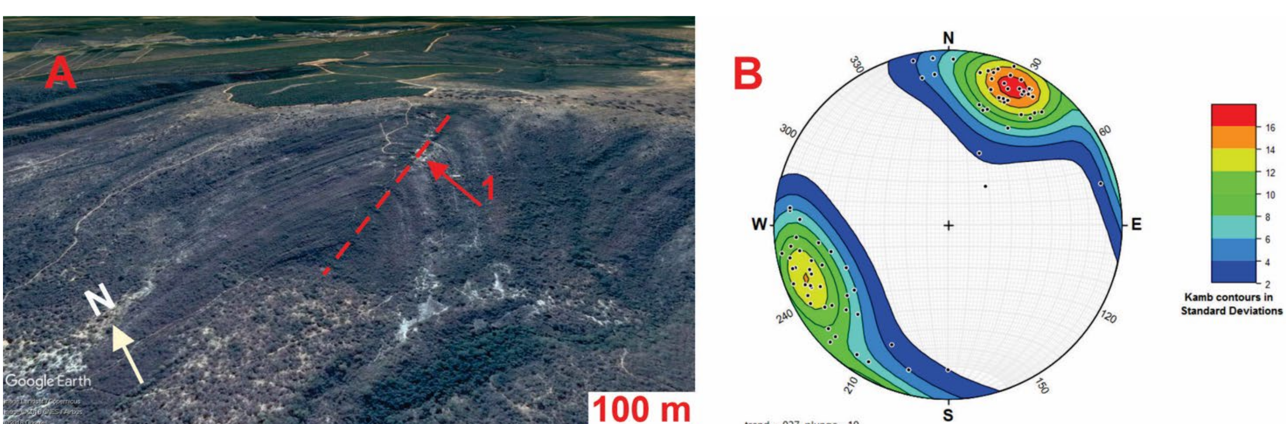


Figure 3. (A) Google Earth view from the tight isoclinal fold present in the quartzites at the Montezuma's amethyst deposit area (red arrow 1), Minas Gerais, where mineralization occurs at the axial surface of the fold (red dashed line). (B) Stereogram of foliation measurements mainly obtained in field by sections perpendicular to the folding axis observed in (A) (n = 70).

rhombohedra showing three faces or with terminal rhombohedra showing six faces. That mineralogical feature gave rise to the names of the last two vein swarms cited.

The crystals with three terminal faces are often enlarged from a narrow, gray to rarely pinkish bottom, to subparallel radiated individuals, whose leveled growth can sometimes produce cavities upon external faces. The samples show repeated growth zones that start in a gray bottom, which gets clearer toward the top and passes to amethyst. The main cavities' filling is also variable, as well as the shape of the terminal rhombohedra. Therefore, white clay fills the druses from the Três Faces veins, while the Seis Faces vein is characterized by a breccia (Cassedanne and Cassedanne, 1976). It is composed of angular, hyaline to clear violet, quartz fragments, and dark amethyst and whitish quartzite pieces. The breccia cement consists of a very thin quartzite, beige to brownish, locally ferruginous or clayey.

Economic aspects have also been described by Bruni and Schobbenhaus Filho (1976) and Fernandes et al. (1982). Both studies noted a main vein, concordant with the host quartzite foliation, measured as E-W/75°S. Considering their timings, those authors have probably addressed to the Três Faces vein. Attitude differences are due to the tight isoclinal folding in the host rock foliation, nowadays observed by means unavailable at that time (Figure 3A), because of the locations where measurements have been done. Bruni and Schobbenhaus Filho (1976) reported an average monthly production of around 900-1,000 kg of superior quality material, hand-picked. As the mining entrance is currently blocked, additional observations could not be made.

As reported in the literature (e.g., Henn and Schultz-Güttler, 2009), amethyst from Montezuma loses its color upon heating at 300°C-350°C. In sequence, at temperatures between 400°C and 500°C, the crystals can acquire a green "prasiolite" color. These data were confirmed according to experiments performed at the CPMTC-IGC/UFMG laboratory.

Coruja (BA)

The Coruja deposit is located in a mountain of the same name (GPS-UTM 815550E and 8322512N, 23L), a local denomination for the Inhaúma Mountains, around 35 km southwest of the municipality of Condeúba, in Bahia state (Figure 4). Mining works started in the 1960s with Badin Mining Company and are currently conducted by a private miner from the region. Although the mountain in this region shows a much more highlighted geomorphological expression (Figure 5A), the folding pattern observed in host quartzites is very similar to that of Montezuma. In this same mineralized area, Fernandes et al. (1982) described the artisanal mines Baixinho, São José do Pequim, and Pastinho.

Host quartzites are also white, fine-grained, and recrystallized, locally micaceous, with attitudes of foliation in the mining area varying between N35-45°E/subvertical. Regional folds, however, have an axial trace near E-W with a steep dip to the NW and SW. Quartz vein swarms, with around 1 m thick for each one, are subconcordant to that foliation, with directions of about N50-60E°/80-85°NW. Bedding has been completely obliterated by deformation tectonics. According to Cassedanne and Cassedanne (1976), mineralization consists of a series of quartz veins rich in amethyst. At the mining site, veins are strongly kaolinized and

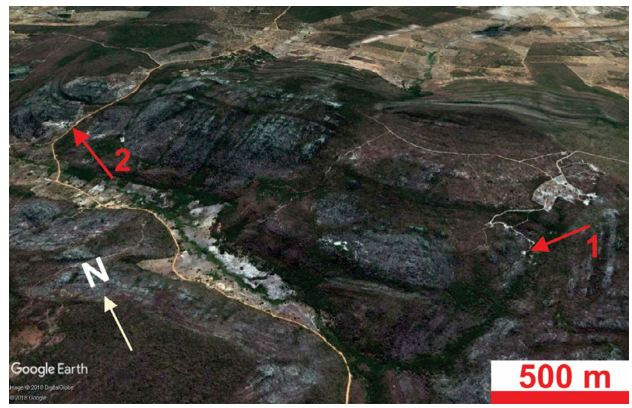
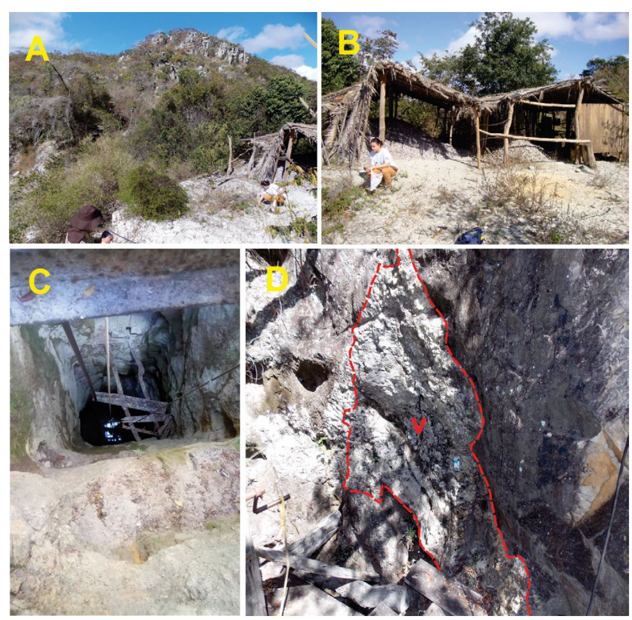


Figure 4. Google Earth view from Coruja Mountain (Bahia), with Coruja (red arrow 1) and Tibério (red arrow 2) deposits.



Source: photos by M. L. S. C. Chaves.

Figure 5. (A) General aspect of the quartzites of the Coruja mountain area, seen from the mine of the same name. (B) Storage of mined material, protected from the sun to avoid color changes. (C) Shaft attaining mineralized vein, currently worked at about 20 m deep. (D) Amethyst vein (v), contact marked with red dashed line, viewed at its superficial exposure.

thus soft enough to be excavated. Piles of extracted material can be observed close to the current mining site (Figure 5B) and are protected from the sun to avoid color changes.

Former artisanal mining works consisted essentially of a wide, 16 m deep, elliptical pit, quite irregular, where three main vein zones were mined. Current miners filled in that pit, and began mining activities in a 1 m thick, subvertical, longitudinal vein using a shaft (Figure 5C); host quartzite is also subvertical with a direction N45°E. Cassedanne and Cassedanne (1976) described a first gallery situated a few meters away from the shaft that reached the amethyst vein in less than 20 m. A vein apophysis can be observed at the surface of the shaft entrance (Figure 5D). Another gallery, 25 m after rounding a curve, reached a small subvertical lens, N45°E, with elongated amethyst crystals. They had well-marked and repeated growth zones: a translucent, colorless, thin bottom, progressively passing to a slightly violet stripe toward the top. Terminal faces appear sprinkled with sand.

The terminal faces of crystals from that lens were covered by a new pale milky to grayish zone formed by multiple tiny parallel or slightly divergent crystals passing to an amethyst color somewhat deeper than the previous one. Such growth phenomena, marked by troubled or impure bands, frequently lead to "hooded" forms that widen toward the top from a very narrow bottom. Flattened crystals show the same growth zonation with upper faces unaffected.

In the 1970s, the maximum monthly production of the mine would have been of about 25 t, with 1.3% of usable stones for ornamental purposes. Irregular specimens slightly predominated above crystallized ones with a 15/13 ratio (Cassedanne and Cassedanne, 1976). Recovered gems often exceeded 20 g after the thinning process, but had a very pale color. However, they showed the characteristic of acquiring an attractive yellow-orange to brown-orange hue upon heating. Such heating treatment was performed in Rio de Janeiro and provided the qualities of "whisky color" and "brandy color," the latter being darker and more appreciated. At local markets, these heat-treated stones were sold under the name of "Bahia topaz."

Heat treatment experiments performed at the CPMTC-IGC/UFMG laboratory have shown that the samples do not undergo any color change until 350°C. At this temperature, fractured crystals begin to decrepitate. Around 400°C-450°C, the elongated crystals' bottom can acquire a greenish or yellow hue after cooling; however, the thin, acicular shape of the samples does not allow gem recovery. Finally, at 600°C, flattened amethyst crystals change to white quartz, with some porcelain aspect and translucent spots, and an irregular fracture net develops along two directions.

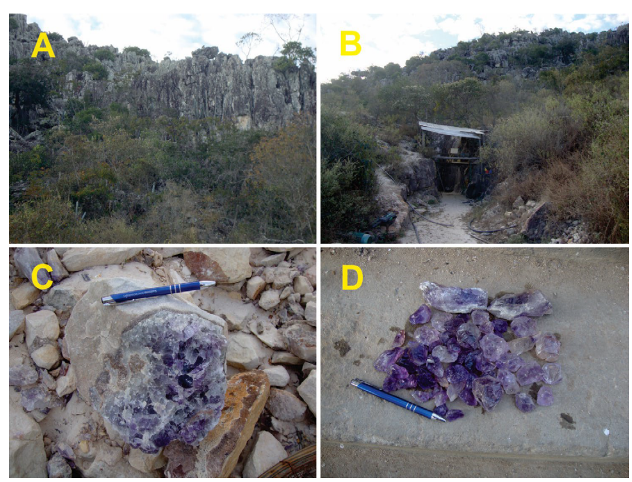
Tibério (BA)

Tibério's artisanal mine is located at the left border of the road connecting Montezuma to Cordeiros, around 22 km south of that town (GPS-UTM 813596E and 8324873N, 23L; Figure 4). It is a more recent mine that has worked since the 1980s. Host quartzites in this area also show ruin-shaped structure (Figure 6A), with remarkable foliation direction of about N20°W/80°SW. The bedding is quite obliterated by this foliation and has an attitude of N45°E/20°SE. This deposit, although in full activity, could not be described in more detail because it was developed in an inclined plane of almost 90°, which is only accessible by a hanging system of vertical descent (Figure 6B). An ornamental quartzite quarry is mined immediately west of the deposit.

Mineralization occurs in narrow fractures of less than 20-30 cm wide (Figure 6C), perpendicular to the foliation that is not evident in this area. At a depth of around 25 m, the mineralization expands into a large cavity with a diameter of approximately 20 m, covered with amethyst crystals that are the current mining focus. The crystals generally have a deep purple color (Figure 6D), and upon heating experiments (CPMTC-IGC/UFMG) do not show any color change until 600°C, when samples turn milky. The purple hue, however, begins fading between 300° and 350°C and disappears from 400°C.

AMETHYST/PRASIOLITE: GENERAL MINERALOGICAL ASPECTS

The causes of purple color in amethyst have long been studied in detail (e.g., Hassan, 1972; Hassan and Cohen, 1974; Nassau, 1978; Henn and Schultz-Güttler, 2009), and



Source: photos by M. L. S. C. Chaves.

Figure 6. (A) Ruin-shaped quartzites showing a vertical foliation that is typical in Tibério's mine. (B) Aspect of the main pit that goes down to the vein being currently mined at around 30 m deep. (C) Part of an amethyst vein in the host quartzite. (D) Hand-selected amethyst parcel with deeper color.

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those authors emphasized the important role of iron and/or manganese ions in color acquisition. According to Webster (1970), in about 1953, it was accidentally discovered that the amethyst found at Montezuma would, when heated, produce a green-colored quartz, and from such treated material, stones have been cut and sold as "prasiolite." This outstanding phenomenon was first mentioned by Pough (1957).

Henn and Schultz-Güttler (2009) stated that until a few years earlier, all of the green quartz used in jeweler's industry was that of heat-treated amethyst, also known as "greened amethyst." The color acquired reportedly results from a heating process of around 400°C-500°C. Lehmann and Bambauer (1973 *apud* Henn and Schultz-Güttler, 2009) have detailed the mechanism of such a transformation process. The original amethyst color was the result of substitution of the unusual Fe^{4+} ion in structural silicon (Si^{4+}) sites; additionally, Fe^{2+} is present in I_4 tetrahedral interstitial sites. Enokihara (2013) noticed that high concentrations of molecular water and hydroxyl are responsible for the formation of a greenish color in colorless quartz after exposure to ionizing radiation. In this regard, further infrared spectroscopy analyses are still needed in order to improve the discussion about the relation between geological context, structural defects, and color changes upon different treatments.

According to Henn and Schultz-Güttler (2009), with initial heating above 350°C, Fe^{4+} and Fe^{2+} (in structural and interstitial sites, respectively) change to Fe^{3+}, and amethyst becomes colorless or yellowish. In amethyst from very rare occurrences, particularly those from Montezuma and Condeúba, overheating between 400°C and 500°C, causes Fe^{3+} reduction in interstitial I_4 sites to Fe^{2+} in I_6 octahedral interstitial sites, and a green olive or sometimes green-yellowish color remains stable until 600°C. Güttler et al. (2011) also discussed the mechanism that causes color changes in amethyst and assigned Fe^{3+} in interstitial I_4 sites as the precursor of the prasiolite color center.

Additionally, Dias (2020) suggested, based on electron paramagnetic resonance experiments, that color changes observed in amethyst after heating and/or irradiation could be related to valence changes between Fe^{3+} and Fe^{4+} ions. Furthermore, Henn and Schultz-Güttler (2009) stated that, due to the increasing lack of Montezuma's material, most of the green quartz currently available in the global market derives from cobalt 60 gamma irradiation treatments on samples from several other locations, including Brazilian ones. It should be noted that prasiolite shows a much greater photostability than green quartz, remaining stable at temperatures of up to 600°C, while green quartz loses color easily under strong ultraviolet light or heating between 150 and 200°C (Correa, 2010).

ADDITIONAL GEOLOGICAL DISCUSSION

The problem of geological mapping involving the Espinhaço Mountain Range and its eastern border units, in northern Minas Gerais and southern Bahia, needs to be unified by the Serviço Geológico do Brasil (SGB-CPRM), since most maps of Minas Gerais assign the quartzites that host the mineralization to the "Macaúbas-Santo Onofre" sequence, with a post-Espinhaço age (Neoproterozoic), whereas in Bahia they are inserted in the "Serra de Inhaúma" unit, with an older, probably Paleoproterozoic age (Inda and Barbosa, 1978; Knauer et al., 2015). Regardless of this unresolved issue, it seems clear that the amethyst mineralization at the three described localities is related to the same geological unit, due to their identical structural behavior on both sides of the border. The main characteristics of the deposits focused on are presented in Table 1.

However, a geological issue remains to be further discussed. Hydrothermal quartz veins already dated in the Espinhaço Mountain Range in Minas Gerais and Bahia, using U-Pb dating method in monazite-(Ce) and xenotime-(Y) (Chaves et al., 2010, 2018, respectively), showed crystallization ages of around 490 Ma, which is a late Brazilian orogeny age (Araçuaí Fold Belt). Hence, in principle amethyst mineralization classically related to the Macaúbas

Table 1. Main information about the three different deposits studied.

Amethyst Deposit	Montezuma	Coruja	Tibério
Mineralization type	Hydrothermal quartz veins with amethyst	Hydrothermal quartz veins with amethyst	Hydrothermal quartz veins/ cavities with amethyst
Municipality/State	Montezuma/Minas Gerais	Condeúba/Bahia	Cordeiros/Bahia
Location UTM latitude	8322350N	8322512N	8324873N
Location UTM longitude	771509E	815550E	813596E
Location UTM zone	23L	23L	23L
Host quartzite bedding attitude	N20°E/20°SE	Not observed (obliterated)	N45°E/20°SE
Host quartzite foliation attitude	N10-20°W/70°SW	N35-45°E/ subvertical	N20°W/80°SW
Veins main thickness	0.70–1.10 m	1 m	0.2–0.3 m
Amethyst color change upon heating	Green	Green/yellow	Colorless

Group in Minas Gerais, such as those from Itamarandiba and Felício dos Santos, could be the same age in these areas as well as in Montezuma (MG) and Condeúba/Cordeiros (BA). Only specific geochronological studies on minerals from the veins themselves in both regions will shed light on this subject.

In the absence of such studies, three possibilities exist:

- two different mineralization ages, an older Paleoproterozoic one involving the deposits of north of Minas Gerais (Montezuma) and south of Bahia (Condeúba/Cordeiros), and a younger Neoproterozoic/Cambrian age for the deposits of Itamarandiba and Felício dos Santos, in addition to others in the Espinhaço region as Buenópolis and Grão Mogol ones (Chaves and Favacho-Silva, 2000);
- a single Neoproterozoic mineralization age for all of the deposits mentioned above, considering a same host geological sequence in the Espinhaço eastern border in both states;
- a single Neoproterozoic mineralization age for all of the deposits mentioned above, but with mineralization being hosted in two sequences of entirely different ages.

CONCLUDING REMARKS

Geological and structural studies conducted on quartzite sequences that host amethyst vein mineralization in the bordering region between Minas Gerais and Bahia states, especially those from the Montezuma (MG) region, demonstrate a clear structural control for the veins. These veins occur associated with folding axes zones imprinted on regional foliation, which show direction around ENE-WSW.

The structural pattern present in the studied area is characterized by folding of the foliation, indicating an additional deformation phase. Such pattern does not exist in amethyst hydrothermal deposits more to the south of MG, corroborating an older age to the mineralization host sequences, Santo Onofre in Minas Gerais and Serra de Inhaúma in BA. However, mineralization ages and a possible relation between different colors acquired upon heat treatments and deposits in a geological/structural context could not be established.

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